Mode-selective toroidal mirrors for unstable resonator planar waveguide and thin slab solid-state lasers

Mode-Selective Toroidal Mirrors for Unstable Resonator Planar Waveguide and Thin Slab Solid-State Lasers

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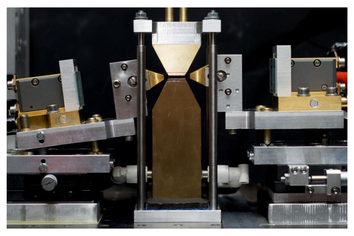
Summary

We have developed two new fabrication methods for mode-selective *highly-curved* toroidal laser mirrors based on laser micromachining of cylindrical substrates *that already have the small lateral curvature (R_L > 1m)* provided by conventional polishing. These mirrors are produced by a two-step CO_2 laser machining process with high resolution ablative laser cutting [1] and then laser polishing [2], or by vaporization of silica in the CO_2 laser smoothing process at higher than usual power. We have produced mirrors with R_T = 32mm and 16mm radius of curvature in the transverse direction and 14mm lateral length for use with the 200µm core height Nd:YAG [3] and a 150µm core Yb:YAG planar waveguide laser respectively. Proof of principle of fabricated mirrors was confirmed in the mode-selective configuration *(Case III)* for the Yb:YAG planar waveguide laser.

Objectives

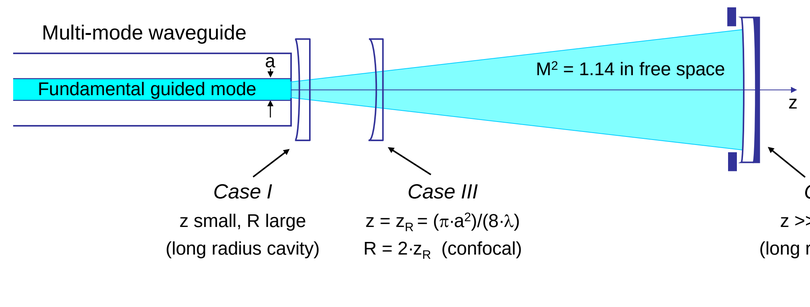
- The use of mode-selective slit-shaped toroidal mirrors for the unstable resonator configuration in planar waveguide or thin slab solid-state lasers.
- Fabrication of highly-curved (R_L/R_T > 10) toroidal mirrors using a CO2 laser for the mode-selective waveguide resonator configuration *(Case III).*
- Investigation of effectiveness of the fabricated mirrors with the Yb:YAG/sapphire planar waveguide laser.

Yb:YAG planar waveguide laser with the pump and cooling system



Low loss configurations for waveguide resonators

We can distinguish three configurations (cases) for waveguide resonators with external mirrors [4], where the coupling losses of the fundamental mode between free-space and the waveguide facet are less than 1%.



Case I: All waveguide modes are efficiently coupled back to the waveguide core – ensuring a multi-mode beam in the transverse axis.

Case II: All the free-space modes are efficiently coupled back to the end-facet – an intercavity aperture is placed in the far field to select the fundamental mode – see for example [3].

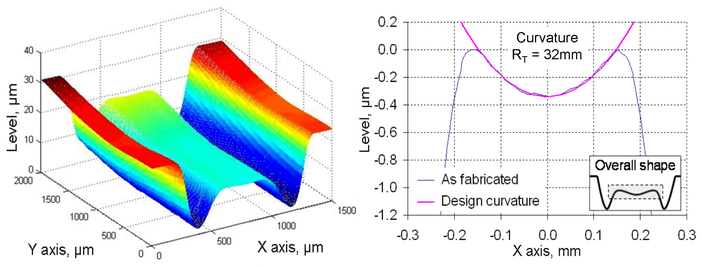
Case III: The higher order modes coupled into free-space are returned into the core with decreasing efficiency – natural mode selectivity and improvement of the times diffraction-limit factor (M^2)

CO_2 laser fabrication of highly curved toroidal resonator mirrors

Technique 1: *A two-step CO_2 laser machining process with high-resolution ablative laser cutting (made by PowerPhotonic Ltd.) and then laser polishing*.

- Silica *cylindrical lens* with 240mm lateral RoC used as a substrate.
- Desired shape and transverse curvature of a mirror obtained by precise ablative laser cutting.
- Roughness of 300µm wide laser-cut mirror removed by localized laser polishing.
- Lateral RoC is decreased by surface stress produced by polishing.

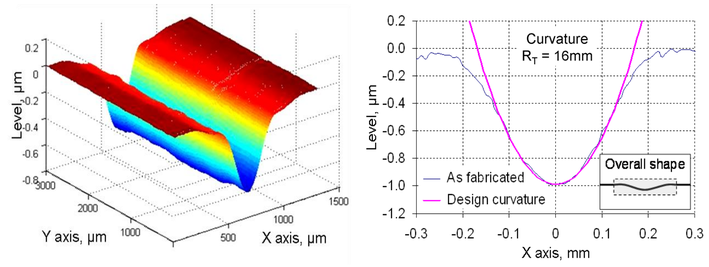
Surface profile and cross-section of a resonator mirror fabricated by laser cutting and laser polishing



Technique 2: *Vaporization of fused silica in the laser polishing process at higher than usual laser power*

- 2mm thick *planar* fused silica used as a substrate.
- 300µm wide trench made by CW raster scan area laser polishing, but at higher than usual laser power.
- Depth of desired profile is controlled by laser power used.

Surface profile and cross-section of a resonator mirror made by vaporization in laser polishing process

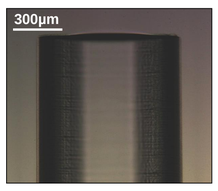


Features of the ablatively-cut toroidal mirrors:

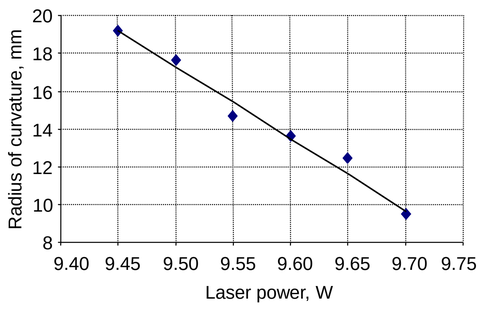
- Toroidal mirrors have 14mm long and 300µm wide optical aperture.
- Transverse radii of curvature, R_T = 20, 32 and 36mm.
- Mirror radius in the lateral direction is well-defined, R_L = 216mm.
- The surrounding rims of reverse curvature and side-grooves designed to disperse higher order laser modes.
- Some low spatial frequency features in the lateral direction that may introduce beam distortion.
- The toroidal mirror with R_T = 32mm matches *Case III* coupling for 200µm core height Nd:YAG planar waveguide laser [3].
- Mirror suitable for the unstable resonator configuration.

Surface roughness ±20nm

Optical microscope image of a laser-cut resonator mirror



Influence of CO_2 laser power on mirror curvature



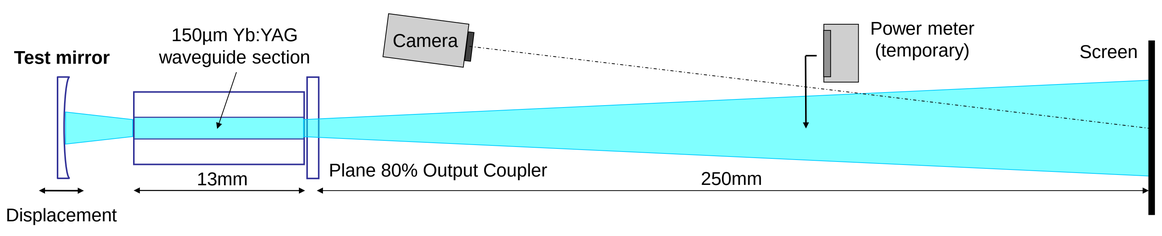
Ultra-low surface roughness ±10nm

Features of the cylinder mirrors made by vaporization:

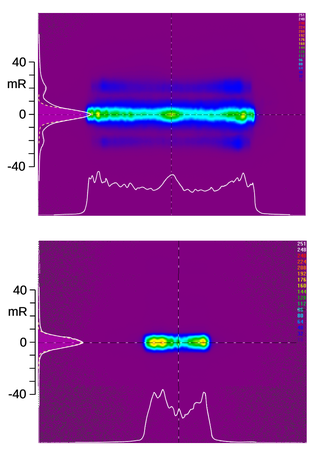
- Small stress RoC in lateral direction, R_L > 2m.
- RoC in transverse direction R_T from 10 to 45mm.
- The mode-selective effect is less pronounced than in the laser-cut mirror but still useful.
- Mirror with R_T = 16mm matches *Case III* coupling for 150µm core height Yb:YAG planar waveguide laser.

Testing of fabricated mirrors with Yb:YAG/Sapphire planar waveguide laser

Test setup for resonator mirrors



Beam images for *the conventional mirrors*



1m RoC spherical rear mirror used in *Case I:*

- Mirror placed 0.5mm from waveguide facet.
- 70 W output power at 35A diode current.
- No mode selectivity.
- Visible group of at least two transverse modes.

15.5mm cylinder mirror used in *Case III:*

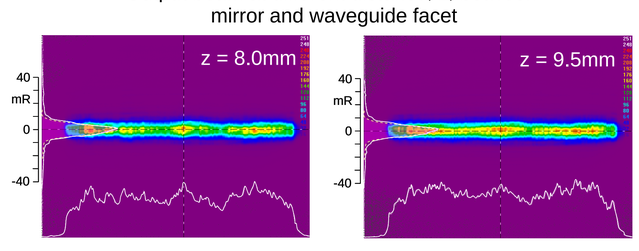
- 95% reflective mirror placed 8mm from waveguide facet.
- Output power reduced to 58W because of ~10W leakage from the test mirror.
- Suppressed high order modes in the transverse direction.
- Unsuitable for unstable resonator configuration – infinite aperture.

Beam images for *the ablatively-cut toroidal mirror* (R_T = 20mm, R_L = 216mm)

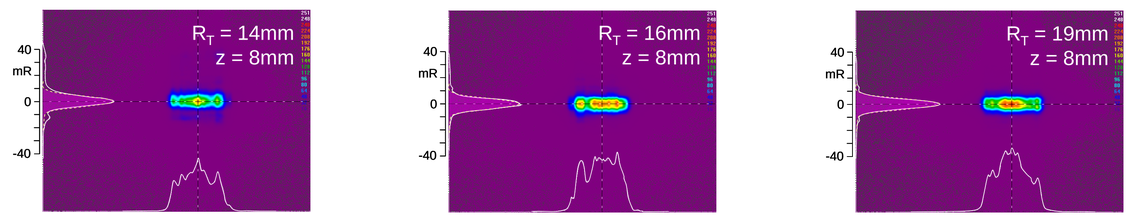
- Transverse curvature slightly smaller than required for *Case III* configuration.
- 40W output power at 35A diode current.
- Mode-selectivity in the transverse direction.

- Appropriate for unstable resonators in planar waveguide or thin slab solid-state lasers.

Output beam at different distance, z, between mirror and waveguide facet



Beam images for *the cylinder mirrors made by vaporization* with different R_T



- Mirror mis-matched *Case III* coupling.
- 46W output at 35A.
- Visible high order modes.

- Mirror matches Case III
- 56W output at 35A.
- Suppressed high order modes in the transverse direction.

- Transverse RoC larger than required.
- 54W output at 35A.
- High order modes appeared.

Conclusion

- We have developed CO_2 laser-based fabrication methods that are capable of produce highly-curved toroidal mirrors with the ratio of R_L/R_T > 10.
- Fabricated mirrors successfully demonstrated mode-selectivity (*Case III*) in a planar waveguide laser.
- Highly-curved slit-shaped toroidal mirrors can be used for the unstable resonator configuration in planar waveguide and thin slab solid-state lasers.

References

[1] G. J. Markillie, H. J. Baker, F. Villarreal, D. R. Hall, *"The effect of vaporization and melt ejection on laser machining of silica glass micro-optical components,"* Applied Optics **41**, 5660 (2002).

[2] K. M. Nowak, H. J. Baker, D. R. Hall, *"Efficient laser polishing of silica micro-optical components,"* Applied Optics **45**, 162 (2006).

[3] J. Xu, I. J. Thomson, J. D. R. Valera, H. J. Baker, A. B. Russell, D. R. Hall, *"A Planar Waveguide Nd:YAG Laser Using Active Q-Switching of a Hybrid Unstable Resonator",* IEEE J. Sel. Top. Quantum Electron. **13**, 638 (2007).

[4] J. J. Degnan, D. R. Hall, *Finite-Aperture Waveguide-Laser Resonators,"* IEEE J. Quantum Electron. **QE-9**, 901 (1973).

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